Effectiveness of Self-Reporting Systems in Enforcement of Environmental Regulations

by

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Game-theoretic models are developed to study systematically the self-monitoring and self-reporting systems that industrial and other enteprises are often required to implement to demonstrate their compliance to environmental regulations. Two enforcement systems are modeled and analyzed in detail using extensive form games. The first system implements self-reporting, by requiring the operator of the firm or facility to report information on its own discharges to the enforcement agency. In the second system, the only enforcement measure is sampling of the discharge and auditing of the records by the enforcement agency. Comparison of Nash equilibria for a range of values of model parameters indicates when self-reporting systems can be effective, and suggests when a self-reporting requirement is a preferable feature of an enforcement system.

Key words : Enforcement, Environmental regulations, Inducing compliance, Non-cooperative game theory

1. Introduction

As awareness of the environmental crisis grows world-wide, stricter environmental laws, regulations, and standards have been introduced in many jurisdictions. Stricter environmental regulations, however, do not always mean that every regulated individual or firm is more likely to comply. Enforcement of regulations, by means of monitoring, auditing, and penalizing, is an essential component of the task of agencies responsible for ensuring compliance. Unfortunately, environmental agencies with very limited resources are commonly required to monitor discharges from scores or even hundreds of facilities, to assess apparent violations, and to carry out enforcement actions as appropriate. Moreover, relatively small penalties are the norm for most convictions, so the deterrence of violations by the threat of heavy fines is rarely practical. The success of environmental regulations therefore depends crucially on the levels of efficiency and effectiveness that the enforcement agency can achieve, despite limited penalties and budgetary constraints that may be severe.

The problems of enforcing environmental regulations have been studied from the viewpoint of micro-economics (Downing and Watson, 1974; Harford, 1978; Viscusi and Zeckhauser, 1979; Linder and McBride, 1984; Harrington, 1988) and game theory (Avenhaus, 1990; Russell, 1990; Kilgour *et al.*, 1992). Essentially, these works analyze the enforcement problem of a regulatory agency as a problem of adjusting the level or amount of discharge to the socially optimal level, by means of enforcement actions that depend on the threat of detection and punishment of violations. Enforcement problems have also been analyzed using the theory of repeated noncooperative games, in order to design (voluntary) enforcement systems that capitalize on cooperation by the regulatory agency and the regulated agents (Scholz, 1984a; Scholz, 1984b; Fukuyama *et al.*, 1994).

Recently, in order to reduce costs, some enforcement agencies have shifted compliance verification activities to the operators being regulated. Specifically, operators are required to monitor their own discharges and report them to the agency. For example, in Canada the Ontario Ministry of Environment and Energy uses self-monitoring systems extensively in compliance assessment for more than 160 industrial direct dischargers. Dischargers monitor their effluents on an agreed-upon basis, and report the data to the Ministry at regular intervals. As enforcement agency, the Ministry then carries out audit procedures such as split-sample comparisons to ensure the reliability of the self-monitored data, as well as verification sampling to detect under-reporting.

Yet it is questionable whether auditing has a significant deterrent effect on careless self-monitoring or data falsification via under-reporting. Because the self-reporting system gives the operator some discretion in the data it reports, it may motivate the operator to report only the most favorable data. Thus, self-reporting is effective only if it is implemented in an incentive-compatible system, in which an operator always makes reasonable efforts to comply by discharging within regulations, to monitor accurately its discharge level, and to report the data it observes without modification.

Some research has been carried out on the effectiveness of self-reporting systems in environmental regulations from a microeconomic viewpoint. This work focuses mainly on conditions that penalty levels balance the enforcement costs of the regulatory agency. For example, Kaplow and Shavell (1994) and Malik (1993) show that an enforcement system with a relatively heavier penalty against false reporting and a relatively lighter penalty against (truthfully reported) violation reduces the regulatory agency's monitoring load, resulting in lower enforcement costs. Harford (1987) analyzes the behavior of a regulated operator as a function of two penalties, against violations of the regulations and against false reporting. The importance of the trade-off between truthful reporting and compliance effort is pointed out. In this research, the behavior of the regulated operator is assumed to be optimal under the enforcement scheme, including penalties and monitoring policy, that is exogeneously determined by the regulatory agency. The behavior of the agency and the counter-actions of the operator are therefore not considered in these models.

The relationships between the enforcement agency and the regulated operator can be described as interactions: actions and counter-actions. For example, when the operator voluntarily complies with the regulation, the agency may use lenient enforcement. On the other hand, when the operator makes only a weak effort to comply, the agency may use stricter enforcement such as more frequent monitoring and more severe penalties. Such strategic behavior by two interacting decision makers can be effectively analyzed only by game theory. By employing game theoretic techniques, key factors in enforcement relationships between regulator and regulatee, such as the incentives and disincentives to truthful reporting, can be modeled explicitly.

The objective of this research is to develop formal game-theoretic models for assessing the effectiveness of self-reporting systems. The game models to be introduced here extend the basic model of enforcement with self-reporting given in Fukuyama *et al.* (1994). Two enforcement systems, with and without self-reporting, are represented abstractly as extensive form games. The Nash equilibria of these games determine the conditions under which the

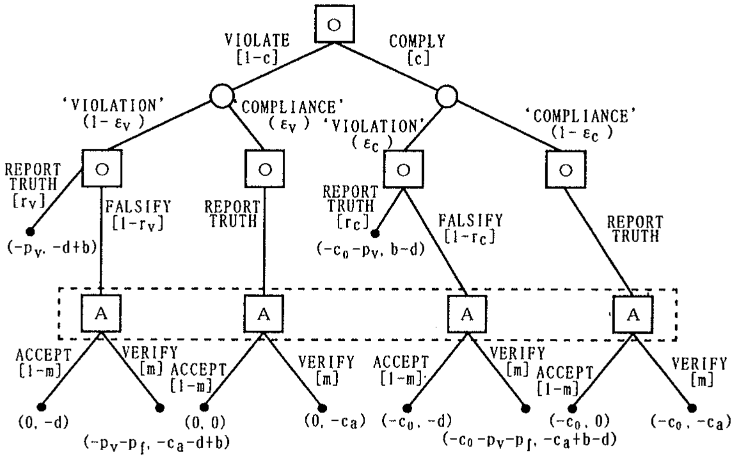

Figure 1: Extensive form game of environmental enforcement with self-reporting systems.

enforcement can be efficient and effective. Furthermore, the equilibria of the two models can be compared to clarify the effect of introducing self-reporting into enforcement.

2. Game Models of Environmental Enforcement

2-1 The Game

In general, the use of self-monitoring and self-reporting systems in the enforcement of environmental standards can be described as follows. The operator monitors its discharges and submits the data to the regulatory agency on a regular basis. To support this reported data, the environmental agency carries out auditing activities, such as split-sample comparisons, as well as verification sampling, including unannounced on-site visits, to verify the self-reported data. If there is evidence of a violation, the inspecting agency can issue a control order, begin legal action in a court, or levy a penalty directly.

Figure 1 shows an extensive game model of a system for enforcing a regulation that incorporates self-reporting. There are two decision makers, called Operator and Agency. Operator represents an industrial firm producing water- or air-borne discharges, and Agency is an environmental agency in charge of regulating Operator's discharge. Agency uses a self-reporting system requiring that Operator monitor its discharge and report the data to Agency. To interpret Figure 1, start from the top and read downward. Each box containing a capital letter represents a decision point for the decision maker designated by that letter. Hence, at the start of the game, Operator [O] must decide whether to *Violate* or *Comply*. Here, *Violate* does not necessarily mean intentional violation, but rather minimal compliance effort, which may result in violations of environmental standards. Likewise, *Comply* means maximal compliance effort. If Operator chooses Comply, the game moves to the lower right subtree, but if Operator chooses Violate, it passes to the lower left. After this decision, Operator self-monitors its discharge levels, producing a report that is either 'Compliance' or 'Violation.' The measurement of discharge level is represented by open-circle nodes in Figure 1. These nodes correspond to random events; the measurement of direct discharge is almost always affected by uncontrollable factors such as dilution, as well as operational, machine, and measurement errors. Because of these exogeneous factors, the resulting compliance status reflects not only Operator's previous Compliance effort level, but also chance (or risk). The exogeneous risk of a faulty measurement is represented by the conditional probabilities of self-monitoring errors, ε_c and ε_v. For example, the probability that an observation results in 'Compliance' for an Operator who chose Comply is $1-\varepsilon_c$.

As shown in Figure 1, Operator's second decision is whether to report the true monitoring results to Agency (*Report Truth*) or to falsify the data (*Falsify*). The first option, Report Truth, does not mean that Operator reports its Compliance effort level, but only its measurement. In particular, it may happen that the data reported by Operator under the Report Truth alternative does not agree with results obtained from independent verification. Note that if Operator's self-monitoring result is 'Compliance,' it has no incentive to falsify; therefore the Falsify option is not shown.

Table 1: Benefit / Cost Parameters

Operator			*Agency*		
c_0	:	Cost of Compliance Effort	c_a	:	Auditing Cost
p_v	:	Penalty for Violation	d	:	Environmental Damage caused by Violation
p_f	:	Penalty for False Report	b	:	Reduction in Damage for Detected Violation

At Operator's second level of decision nodes, its alternative choice, Falsify, means intentional falsification and/or fabrication of data, and may also include improperly gathered data. By applying proper monitoring procedures in a careless or negligent manner, or by using improper procedures, Operator may obtain data (without explicit falsification) that are far different from what should have been obtained. If Operator decides to Violate initially (so that the game is in the lower lefthand subtree) and then 'Nature' produces a measurement of 'Violation,' then Operator must decide whether to Report Truth (leftmost branch of the tree) or Falsify. Note that, because Operator chose Violate initially, the Report Truth option in this subtree implies the admission that the original choice was Violate. Thus, if Operator chooses the leftmost path, Agency does not need to monitor, for it knows that Operator is in violation.

On the other hand, Agency, represented by [A], in Figure 1 has only one decision, to verify the self-reported data (*Verify*), or not (*Accept*). The verification process is assumed to be perfect in the sense that it enables Agency to determine for certain whether Operator observed 'Compliance' or 'Violation,' and therefore whether Operator's second decision was Report Truth or Falsify. However, the verification process is imperfect in another sense; it is impossible for Agency to determine precisely Operator's level of compliance effort, i.e. its original decision to Violate or Comply.

Note that the four decision points for Agency in the lower part of Figure 1 are enclosed by a dotted line to indicate that they lie in the same information set. Consequently, Agency does not know the prior events in the game when it makes its choice. In other words, Agency must decide whether to Verify or Accept without any information about Operator's decision to Violate or Comply. If Operator originally chose Violate, and if the monitoring result was 'Violation,' and if Operator then decided to Report Truth (left node), then Agency can infer everything that happened previously, including all of Operator's decisions.

The game has ten possible outcomes represented by the solid circles in Figure 1. For example, if Operator chooses Violate first, then monitoring produces 'Violation,' then Operator chooses Falsify, and finally Agency chooses Verify, then the game results in detected violation. The expected utility payoff of each outcome for Operator and Agency is indicated in Figure 1 adjacent to each terminal node; the first entry in parentheses is the payoff for Operator, and the second for Agency. The cost and benefit factors included in these payoffs are measured as von Neumann and Morgenstern utilities and are constructed from the parameters given in Table 1. Note that all symbols represent positive numbers, so a payoff parameter with a negative sign represents a cost. The case in which Operator chooses Violate, then monitoring produces 'Compliance,' then Operator chooses Report Truth, and finally Agency chooses Accept, is assumed to be the base case with payoff $(0,0)$. [Note that in this case compliance is reached without any effort by Operator and Agency.] For example, if Operator chooses Violate, resulting in 'Violation,' then chooses Falsify, and Agency chooses Verify, then Operator's payoff is $-p_v - p_f$, where the penalty for violation is p_v and the penalty for falsification is p_f; Agency receives $-c_a - d + b$, reflecting the damage caused by the violation ($-d$), the verification monitoring costs ($-c_a$), and the benefit of detecting violation (b).

In this Self-Reporting Game, the players' strategic choices are represented by decision variables: c is the probability that Operator chooses Comply, so $(1-c)$ is the probability of Violate; r_c is the probability that Operator chooses Report Truth when it has already chosen Comply, and $(1-r_c)$ that it chooses Falsify; r_v is the probability that Operator chooses Report Truth when it had already chosen Violate, $(1-r_v)$ the probability that it chooses Falsify; and m is the probability that Agency chooses Verify, so that $(1-m)$ is the probability that Agency chooses Accept. If a decision variable is neither 1 nor 0, then it is interpreted as the probability that the decision maker chooses accordingly. For example, if $0 < c < 1$, then c is the probability that Operator chooses Comply, so that $1-c$ is the probability of Violate.

The expected payoff for Operator, U_O, can be expressed as

$$U_O = c \cdot \left[-c_0 + \varepsilon_c \left[r_c\{m(c_r + p_f) - c_r\} - m(c_r + p_f)\right]\right]$$

$$+(1-c)(1-\varepsilon_v)\{[m(p_v+p_f)-p_v]\,r_v-m(p_v+p_f)\}\,. \quad (1)$$

Similarly, the expected payoff for Agency is

$$\begin{aligned} U_A &= -m\cdot c_a + c\cdot\varepsilon_c[m\{(c_a+c_p)r_c-c_p\}-c_pr_c-d] \\ &\quad +(1-c)(1-\varepsilon_v)[m\{(c_a-b)r_v+b\}+b\cdot r_v-d]. \end{aligned} \quad (2)$$

The players, Operator and Agency, choose their decision variables, c, r_c, and r_v (for Operator) and m (for Agency) to maximize their expected payoffs. In the analysis, Nash Equilibrium is the primary solution concept.

2-2 Equilibrium Analyses

A Nash equilibrium, $(m^*;c^*,r_c^*,r_v^*)$, is a combination of complete strategies, for Operator and for Agency, such that each player's strategy is a best response to the other. We consider only cases in which $c_a-(1-\varepsilon_v)b<0$, so that Agency has an incentive to audit.

A Nash equilibrium is obtained by considering the stable combination of the *best reply correspondences* for the all players. The best reply correspondence is a complete mapping of the strategy set of the opponent(s) on his/her own strategy set, which brings about the best expected payoff. First, when $c_0+\varepsilon_cp_v>(1-\varepsilon_v)p_v$, it can be shown that the only possible best reply correspondence for Operator is Violation, i.e. $c=0$. Accordingly, our equilibrium analyses will concentrate on the case when $c_0+\varepsilon_cp_v<(1-\varepsilon_v)p_v$. This condition implies that $(1-\varepsilon_c-\varepsilon_v)>c_0/p_v(>0)$. (For the detailed derivation and calculation of Nash equilibrium of the self-reporting game, refer to Appendix (A-1)).

The equilibria of the self-reporting game model have two possible forms, depending on the relative values of some cost and benefit parameters. The complete list of possible equilibria is given in Table 2. Note that the game has a unique Nash equilibrium in each case.

Table 2: Nash Equilibria of Enforcement Game with Self-Reporting.

[1-1] When $c_a-(1-\varepsilon_v)b<0$ and $c_a-\varepsilon_cb>0$

m^*	c^*	r_c^*	r_v^*
$\frac{c_0}{(1-\varepsilon_c-\varepsilon_v)(p_f+p_v)}$	$\frac{c_a-(1-\varepsilon_v)b}{(\varepsilon_c+\varepsilon_v-1)b}$	0	0

[1-2] When $c_a-(1-\varepsilon_v)b<0$ and $c_a-\varepsilon_cb<0$

m^*	c^*	r_c^*	r_v^*
$\frac{p_v}{p_v+p_f}$	1	$\frac{c_a-\varepsilon_cb}{\varepsilon_c(c_a-b)}$	$[0,1]$

Clearly, no equilibrium includes truthful reporting. The equilibrium in case [1-1] involves (some) compliance by Operator $(0<c^*<1)$. Case [1-2] has, as its unique equilibrium, full compliance effort, $c^*=1$. This case is realized when the ratio of auditing cost (c_a) to benefit of detection (b) is less than the probability of observing Violation, whether that observation follows low compliance effort $(1-\varepsilon_v)$, or high compliance effort (ε_c).

3. Enforcement without Self-Reporting

Figure 2 shows an extensive form game of environmental enforcement without self-reporting. The model can be obtained from the game of Figure 1 by simply removing Operator's self-reporting decision points (*Report Truth* or *Falsify*). The expected payoffs of Operator and Agency are given as follows.

$$\begin{aligned} U_O &= c\cdot[-c_0+\varepsilon_c[\{m(p_v+p_f)-p_v\}r_c-m(p_v+p_f)]] \\ &\quad +(1-c)(1-\varepsilon_v)[\{m(p_v+p_f)-p_v\}r_v-m(p_v+p_f)] \end{aligned} \quad (3)$$

$$\begin{aligned} U_A &= -m\cdot c_a + c\cdot\varepsilon_c[m\{(c_a-b)r_c+b\}+b\cdot r_c-d] \\ &\quad +(1-c)(1-\varepsilon_v)[m\{(c_a-b)r_v+b\}+b\cdot r_v-d] \end{aligned} \quad (4)$$

This game has eight possible outcomes, denoted by solid circles in Figure 2. When, Agency has some incentive to Monitor $(p_v<c_0/(1-\varepsilon_v-\varepsilon_c))$ and Operator has some incentive to Comply $((1-\varepsilon_v)>c_a/b)$, it can be shown that the model without self-reporting of Figure 2 always has a unique Nash equilibrium (refer to Appendix (A-2) for details), in one of the two forms shown in Table 3.

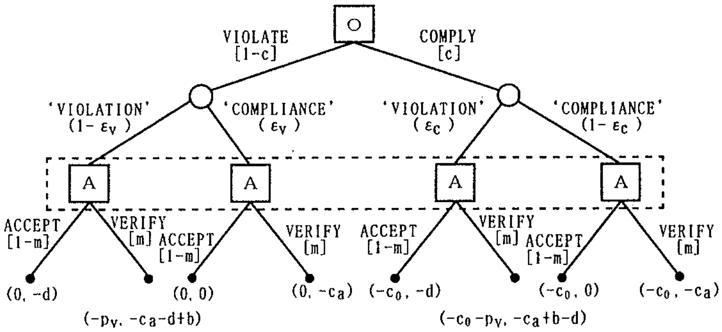

Figure 2: Extensive form game of environmental enforcement without self-reporting.

Which case applies depends on the cost/benefit parameters. For example, in Case [2-1] the expected benefits from regulation exceed the auditing costs. The results are interpreted below.

4. Results and Conclusion

The defining conditions for Case [1-1] in Table 2 and Case [2-1] in Table 2 are identical; they place exactly the same conditions on the cost/benefit parameters. Similarly, Case [1-2] in Table 2 and Case [2-2] in Table 2 are the same. We will refer to Cases [1-1] and [2-1] as the high audit cost cases, and Cases [1-2] and [2-2] as the low audit cost cases. By comparing the two high audit cost cases, and the two low audit cost cases, we can assess the effects of self-reporting systems on enforcement.

In the high audit cost case, the expected benefit from regulation, whether compliance effort is high or low, is less than the auditing costs for the enforcement agency. Whether there is self-reporting (see Case [1-2] of Table 2) or not (Case [2-2] of Table 3), the operator's compliance effort level is identical, and equals $c^* = \frac{(1-\varepsilon_v b - c_a)}{(1-\varepsilon_c-\varepsilon_v)b}$. However, less monitoring in required with self-reporting. Note that the monitoring probability m^* in [1-1] of Table 2 is less than the monitoring probability m^* in Case [2-1] of Table 3. In other words, with self-reporting, a lower level of monitoring effort is required to achieve the same level of compliance effort by the operator.

In the low audit cost case, the expected benefit from regulation always exceeds the auditing costs. Under enforcement without self-reporting (see Case [2-1] of Table 3), the agency induces full compliance effort from the operator ($c^* = 1$), but only by the maximum monitoring ($m^* = 1$). If self-reporting is included in the enforcement system (see Case [1-1] of Table 2), full compliance $c^* = 1$ is sustained by the less-than-certain monitoring level $m^* = \frac{p_v}{p_v+p_f} < 1$. In other words, the self-reporting system reduces the monitoring level required to motivate the operator to comply fully, resulting in a reduction in enforcement costs. Moreover, it is clear from Case [1-2] that an increase in the penalty against false reporting, p_f, can reduce the level of monitoring required to achieve full compliance.

Finally, it is obvious that the shift from the high audit cost case to the low audit cost case can be brought about by reducing the cost of monitoring and auditing c_a. The effect is important, as the resulting Nash equilibrium moves from probabilistic compliance to certain (full) compliance. Therefore, the innovations in monitoring technology are to be welcomed. They can be a key factor in reducing costs and increasing effectiveness in environmental enforcement.

Table 3: Nash Equilibria of Enforcement Game without Self-Reporting.

[2-1] When $c_a - (1-\varepsilon_v)b < 0$ and $c_a - \varepsilon_c b > 0$.

m^*	c^*
$\frac{c_0}{(1-\varepsilon_c-\varepsilon_v)p_v}$	$\frac{(1-\varepsilon_v)b-c_a}{(1-\varepsilon_c-\varepsilon_v)b}$

[2-2] When $c_a - (1-\varepsilon_v)b < 0$ and $c_a - \varepsilon_c b < 0$.

m^*	c^*
1	1

In this paper, the effectiveness of self-reporting is analyzed by constructing, analyzing, and comparing two extensive game models of enforcement. These models are identical, except that one includes self-reporting and the other does nt. This methodology has clarified the conditions under which self-reporting systems can be successful in improving the effectiveness, and reducing the costs, of enforcing environmental regulations.

Appendix: Equilibrium Calculations

(A-1) *The Game with Self-Reporting*

(1) The Best Reply Correspondences of Operator

First, induce the *best reply correspondences* for Operator, $(c^{best}, r_c^{best}, r_v^{best})(m)$. From (3),

$$U_{Oc}(m) = \frac{\partial U_O}{\partial c} = -c_0 + \varepsilon_c [\{m(p_v + p_f) - p_v\}r_c - m(p_v + p_f)] - (1 - \varepsilon_v)[\{m(p_v + p_f) - p_v\}r_v - m(p_v + p_f)] \quad (5)$$

$$U_{Or_c}(m) = \frac{\partial U_O}{\partial r_c} = c\varepsilon_c\{m(p_v + p_f) - p_v\} \quad (6)$$

$$U_{Or_v}(m) = \frac{\partial U_O}{\partial r_v} = (1 - c)(1 - \varepsilon_v)\{m(p_v + p_f) - p_v\} \quad (7)$$

Notice from (3) that the decision variable r_c affects Operator's expected payoff only when Operator does not always violate (i.e. $c > 0$). Similarly, the value of r_v affects Operator's expected payoff only when $c < 1$. Also, because $0 \leq c \leq 1$, the strategy that brings about the maximum expected payoff for Operator always appears either at $c = 0$ or $c = 1$. Thus, the *best reply correspondences* for Operator can be assessed by studying when $c = 0$ and $c = 1$.

First $c = 1$,

$$U_{Or_c} = \varepsilon_c\{m(p_v + p_f) - p_v\} \quad (8)$$

Consequently

$$U_{Or_c} \begin{matrix} > \\ = \\ < \end{matrix} \text{ according as } m \begin{matrix} > \\ = \\ < \end{matrix} \frac{p_v}{p_v + p_f} \quad (9)$$

Also, When $c = 0$,

$$U_{Or_v} = (1 - \varepsilon_v)\{m(p_v + p_f) - p_v\} \quad (10)$$

Consequently

$$U_{Or_v} \begin{matrix} > \\ = \\ < \end{matrix} \text{ according as } m \begin{matrix} > \\ = \\ < \end{matrix} \frac{p_v}{p_v + p_f} \quad (11)$$

Let U_0 be expressed with the decision variables explicitly as $U_O(c, r_c, r_v; m)$. When $c = 1$,

$$U_O(1, 1, -; m) = -c_0 + \varepsilon_c p_v$$
$$U_O(1, 0, -; m) = -c_0 - \varepsilon_c(p_v + p_f)m$$

When $c = 0$,

$$U_O(0, -, 1; m) = -(1 - \varepsilon_v)p_v$$
$$U_O(0, -, 0; m) = -(1 - \varepsilon_v)(p_v + p_f)m$$

Here, if $m > p_v/(p_v + p_f)$, then the truth-reporting is always better off, or $U_O(1, 1, -; m) > U_O(1, 0, -; m)$ and $U_O(0, -, 1; m) > U_O(0, -, 0; m)$. Here the difference of the maximum expected payoffs when complying and violating is given by $U_O(1, 1, -; m) - U_O(0, -, 1; m) = -c_0 - \varepsilon_c p_v + (1 - \varepsilon_v)p_v$. Else if $m < p_v/(p_v + p_f)$, then falsification is always better, or $U_O(1, 0, -; m) > U_O(1, 1, -; m)$ and $U_O(0, -, 0; m) > U_O(0, -, 1; m)$. Here the difference is given by $U_O(1, 0, -; m) - U_O(0, -, 0; m) = -c0 + (p_v + p_f)m(1 - \varepsilon_v - \varepsilon_c)$

Then, it is verified that the following gives the best reply correspondences for Operator, $(c^{best}, r_c^{best}, r_v^{best})(m)$. When $c_0 + \varepsilon_c \cdot p_v > (1 - \varepsilon_v)p_v$

$$(c^{best}, r_c^{best}, r_v^{best})(m) = \begin{cases} (\{0\}, [0, 1], \{0\}) & \text{if } m < p_v/(p_v + p_f) \\ (\{0\}, [0, 1], [0, 1]) & \text{if } m = p_v/(p_v + p_f) \\ (\{0\}, [0, 1], \{1\}) & \text{if } m > p_v/(p_v + p_f) \end{cases} \quad (12)$$

When $c_0 + \varepsilon_c \cdot p_v < (1-\varepsilon_v)p_v$

$$(c^{best}, r_c^{best}, r_v^{best})(m) = \begin{cases} (\{0\},[0,1],\{0\}) & \text{if } m < \frac{c_0}{(1-\varepsilon_c-\varepsilon_v)(p_v+p_f)} \\ (\{0\},[0,1],[0,1]),(\{1\},\{0\},[0,1]),([0,1],\{0\},\{0\}) & \text{if } m = \frac{c_0}{(1-\varepsilon_c-\varepsilon_v)(p_v+p_f)} \\ (\{1\},\{0\},[0,1]) & \text{if } \frac{c_0}{(1-\varepsilon_c-\varepsilon_v)(p_v+p_f)} < m < \frac{p_v}{p_v+p_f} \\ (\{1\},[0,1],[0,1]) & \text{if } m = \frac{p_v}{p_v+p_f} \\ (\{1\},\{1\},[0,1]) & \text{if } \frac{p_v}{p_v+p_f} < m < 1 \end{cases} \quad (13)$$

(2) The Best Reply Correspondences of Agency
From (4),

$$U_{Am}(c) = \frac{\partial U_A}{\partial m} = \frac{\partial U_A}{\partial m} = [\varepsilon_c\{b(1-r_c)+c_a r_c\} - (1-\varepsilon_v)\{b(1-r_v)+c_a r_v\}]c - [c_a - (1-\varepsilon_v)\{b(1-r_v)+c_a r_v\}] \quad (14)$$

Because $U_{Am}(c)$ is linear in c and $0 \le c \le 1$, the sign of $U_{Am}(c)$ can be assessed by studying $U_{Am}(0)$ and $U_{Am}(1)$. Now,

$$\begin{aligned} U_{Am}(0) &= -c_a + (1-\varepsilon_v)[b(1-r_v)+c_a r_v] \\ &= (1-\varepsilon_v)[-(c_a)/(1-\varepsilon_v) + b - (b-c_a)r_v] \quad (15) \\ U_{Am}(1) &= (\varepsilon_c b - c_a) + \varepsilon_c(c_a - b)r_c \quad (16) \end{aligned}$$

because $1-\varepsilon_v > 0$. Consequently,

$$U_{Am}(0) \begin{matrix} > \\ = \\ < \end{matrix} 0 \text{ according as } r_v(b-c_a) \begin{matrix} < \\ = \\ > \end{matrix} b - \frac{c_a}{1-\varepsilon v} \quad (17)$$

First suppose $b \le c_a$. Because $c_a < c_a/(1-\varepsilon_v)$, it follows that $0 \ge b - c_a > b - c_a/(1-\varepsilon_v)$. Therefore, for any r_v satisfying $0 \le r_v \le 1$, $0 \ge r_v(b-c_a) \ge b - c_a > b - c_a/(1-\varepsilon_v)$ so that $U_{Am}(0) < 0$ by (17).

Next, suppose $c_a < b < c_a/(1-\varepsilon_v)$. Then, for any r_v, $r_v(b-c_a) \ge 0 > b - c_a/(1-\varepsilon_v)$. By (17), $U_{Am}(0) < 0$. Finally, suppose $b \ge c_a/(1-\varepsilon_v)$. Then it is easy to verify that $U_{Am}(0) \begin{matrix} > \\ = \\ < \end{matrix}$ according as $r_v \begin{matrix} < \\ = \\ > \end{matrix} b(1-\varepsilon_v) - c_a/\{(1-\varepsilon_v)(b-c_a)\}$.

Next, from (16),

$$U_{Am}(1) \begin{matrix} > \\ = \\ < \end{matrix} 0 \text{ according as } r_c(b-c_a) \begin{matrix} < \\ = \\ > \end{matrix} b - \frac{c_a}{\varepsilon_c} \quad (18)$$

Similar to the case for $U_{Am}(0)$, the following results are obtained. First when $b \le c_a$, $U_{Am}(1) < 0$. When $c_a < b < \frac{c_a}{\varepsilon_c}$, $U_{Am}(1) < 0$. Finally when $b \ge c_a/\varepsilon_c$, $U_{Am}(1) \begin{matrix} > \\ = \\ < \end{matrix}$ according as $r_c \begin{matrix} < \\ = \\ > \end{matrix} \{b\varepsilon_c - c_a\}/\{\varepsilon_c(b-c_a)\}$.

As a result, the best reply correspondences for Agency, $m^{best}(c, r_c, r_v)$, are given as follows.

· when $c_a - b > 0$: $m^{best}(c, r_c, r_v) = 0$

· when $c_a - (1-\varepsilon_v)b > 0$, $c_a - \varepsilon_c b > 0$, and $c_a - b < 0$: $m^{best}(c, r_c, r_v) = 0$
· when $c_a - (1-\varepsilon_v)b > 0$ and $c_a - \varepsilon_c b < 0$. There are three possible cases.
$m^{best}(c, r_c, r_v) = 0$ according as $r_c > \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}$

$$m^{best}(c, r_c, r_v) = \begin{matrix} 0 \\ [0,1] \\ 1 \end{matrix} \quad c \begin{matrix} < \\ = \\ > \end{matrix} \gamma \text{ and } r_c < \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}$$

$$m^{best}(c, r_c, r_v) = \begin{matrix} [0,1] \\ 0 \end{matrix} \text{ according as } c \begin{matrix} = \\ < \end{matrix} 1 \text{ and } r_c = \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}$$

where $\gamma = \{c_a - (1-\varepsilon_v)\{b(1-r_v) + r_v c_a\}\}/\{\varepsilon_c\{b(1-r_c) + c_a r_c\} - (1-\varepsilon_v)\{b(1-r_v) + c_a r_v\}\}$.

· when $c_a - (1-\varepsilon_v)b < 0$ and $c_a - \varepsilon_c b > 0$. There are three possible cases.

$m^{best}(c, r_c, r_v) = 0$ according as $r_v > \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} 1 \\ [0,1] \\ 0 \end{array} \text{ according as } c \begin{array}{c} < \\ = \\ > \end{array} \gamma \text{ and } r_v < \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} [0,1] \\ 0 \end{array} \text{ according as } c \begin{array}{c} = \\ > \end{array} 0 \text{ and } r_v = \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

· when $c_a - (1-\varepsilon_v)b < 0$ and $c_a - \varepsilon_c b < 0$

There are nine possible cases.

$$m^{best}(c, r_c, r_v) = \left\{ \begin{array}{c} 0 \\ [0,1] \\ 1 \end{array} \right\} \text{ according as } c \begin{array}{c} < \\ = \\ > \end{array} \gamma,\ r_c < \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\} \text{ and } r_v > \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$m^{best}(c, r_c, r_v) = 0$ according as $r_c > \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}$ and $r_v > \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} [0,1] \\ 0 \end{array} \text{ according as } c \begin{array}{c} = \\ < \end{array} 1,\ r_c = \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\} \text{ and } r_v > \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$m^{best}(c, r_c, r_v) = 1$ according as $r_c < \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}$ and $r_v < \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} 1 \\ [0,1] \\ 0 \end{array} \text{ according as } c \begin{array}{c} < \\ = \\ > \end{array} \gamma \text{ and } r_c > \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\} \text{ and } r_v < \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} [0,1] \\ 1 \end{array} \text{ according as } c \begin{array}{c} = \\ < \end{array} 1,\ r_c = \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\} \text{ and } r_v < \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} [0,1] \\ 1 \end{array} \text{ according as } c \begin{array}{c} = \\ > \end{array} 0,\ r_c < \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\} \text{ and } r_v = \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$$m^{best}(c, r_c, r_v) = \begin{array}{c} [0,1] \\ 0 \end{array} \text{ according as } c \begin{array}{c} = \\ > \end{array} 0,\ r_c > \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\} \text{ and } r_v = \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$$

$m^{best}(c, r_c, r_v) =]0,1]$ according as $r_c = \{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}$ and $r_v = \{c_a - (1-\varepsilon_v)b\}/\{(1-\varepsilon_v)(c_a - b)\}$

(3) Equilibria of the Game

Notice that a Nash equilibrium of the game consists of a combination of mutually inclusive best responses by both Operator and Agency. We especially consider the equilibria of meaningful cases where Agency has incentive to audit, $c_a - b < 0$.

As you can see in equation (12), when $c_0 + \varepsilon_c p_v > (1-\varepsilon_v)p_v$ the only possible best response for Operator is Violation, $c^{best} = 0$. Accordingly, our equilibrium analyses will concentrate only on the cases when $c_0 + \varepsilon_c p_v < (1-\varepsilon_v)p_v$ (see equation (13)). This condition also implies that $(1 - \varepsilon_c - \varepsilon_v) > \frac{c_0}{p_v} > 0$.

By studying the stable combination of the best reply correspondences for Agency and Operator obtained in A-1-(1) and A-1-(2), the two possible Nash equilibria given in Table 2 can be obtained under the parameter assumptions.

I) When $c_a - (1-\varepsilon_v)b > 0$ and $c_a - \varepsilon_c b > 0$

$\{m^*, c^*, r_c^*, r_v^*\} = \{\{0\}, \{0\}, [0,1], \{0\}\}$

II) When $c_a - (1-\varepsilon_v)b < 0$ and $c_a - \varepsilon_c b > 0$

$\{m^*, c^*, r_c^*, r_v^*\} = \{\{\{c_0\}/\{(1-\varepsilon_c-\varepsilon_v)(p_f + p_v)\}\}, \{\{c_a - (1-\varepsilon_v)b\}/\{(\varepsilon_c + \varepsilon_v - 1)b\}\}, \{0\}, \{0\}\}$

III) When $c_a - (1-\varepsilon_v)b < 0$ and $c_a - \varepsilon_c b < 0$

$\{m^*, c^*, r_c^*, r_v^*\} = \{\{p_v/\{p_v + p_f\}\}, \{1\}, \{\{c_a - \varepsilon_c b\}/\{\varepsilon_c(c_a - b)\}\}, [0,1]\}$

(A-2) *The Game without Self-Reporting*

(1) Best Reply Correspondence of Operator

From (3),

$$U_{Oc}(m) = \frac{\partial U_O}{\partial c} = (1 - \varepsilon_v - \varepsilon_c)p_v m - c_0 \tag{19}$$

Because $U_{Oc}(m)$ is linear in m and $0 \leq m \leq 1$, the sign of $U_{Oc}(m)$ can be assessed by studying $U_{Fc}(0)$ and $U_{Fc}(1)$. Now,

$$U_{Oc}(0) = -c_0 < 0 \tag{20}$$

Also,

$$U_{Oc}(1) = (1 - \varepsilon_v - \varepsilon_c)p_v - c_0 < 0 \tag{21}$$

Assume here that $1-\varepsilon_v-\varepsilon_c>0$. Consequently

$$U_{Oc}(1) \begin{matrix} > \\ = \\ < \end{matrix} 0 \text{ according as } p_v \begin{matrix} > \\ = \\ < \end{matrix} \frac{c_0}{1-\varepsilon_v-\varepsilon_c} \tag{22}$$

From (20) and (22), there are three possible combination of the signs of $U_{Oc}(0)$ and $U_{Oc}(1)$. For each case, the best reply correspondence can be defined as follows.

· When $p_v > c_0/(1-\varepsilon_v-\varepsilon_c)$, $U_{Oc}(m)<0$ therefore $c^{best}=0$

· When $p_v = c_0/(1-\varepsilon_v-\varepsilon_c)$, $U_{Oc}(m) \begin{matrix} < \\ = \end{matrix} 0$ according as $m \begin{matrix} \in \\ = \end{matrix} \begin{matrix} [0,1) \\ 1 \end{matrix}$, and therefore $c^{best} = \begin{matrix} 0 \\ [0,1] \end{matrix}$ according as $m \in \begin{matrix} [0,1) \\ 1 \end{matrix}$

· When $p_v < c_0/(1-\varepsilon_v-\varepsilon_c)$, $U_{Fc}(m) \begin{matrix} < \\ = \\ > \end{matrix} 0$ according as $\begin{matrix} m < c_0/\{(1-\varepsilon_v-\varepsilon_c)p_v\} \\ m = c_0/\{(1-\varepsilon_v-\varepsilon_c)p_v\} \\ m > c_0/\{(1-\varepsilon_v-\varepsilon_c)p_v\} \end{matrix}$

and therefore, $c^{best}(m) = \begin{cases} \{0\} & \text{if } m<\lambda_1 \\ [0,1] & \text{if } m=\lambda_1 \\ \{1\} & \text{if } m>\lambda_1 \end{cases}$ where $\lambda_1 = c_0/\{(1-\varepsilon_v-\varepsilon_c)pv\}$

On the other hand, for Agency, from (4),

$$U_{Am}(c) = \frac{\partial U_A}{\partial m} = -(1-\varepsilon_v-\varepsilon_c)bc + (1-\varepsilon_v)b - c_a \tag{23}$$

Similar to the analyses of U_{Oc} for the best reply correspondences, $U_{Am}(1)$ and $U_{Am}(0)$ are studied below to get the best reply correspondences for Agency. Now,

$$U_{Am}(0) = (1-\varepsilon_v)b - c_a \tag{24}$$

We know that $(1-\varepsilon_v)>0$. Consequently $U_{Am}(0) \begin{matrix} > \\ = \\ < \end{matrix} 0$ according as $(1-\varepsilon_v) \begin{matrix} > \\ = \\ < \end{matrix} c_a/b$.

Also,

$$U_{Am}(1) = \varepsilon_c b - c_a \tag{25}$$

Consequently

$$U_{Am}(1) \begin{matrix} > \\ = \\ < \end{matrix} 0\text{according as}\varepsilon_c \begin{matrix} > \\ = \\ < \end{matrix} c_a/b \tag{26}$$

From (24) and (25), there are nine possible combinations of $U_{Am}(0)$ and $U_{Am}(1)$. The corresponding best reply correspondences of Agency $m^{best}(c)$ are then given as follows.

· When $(1-\varepsilon_v)>c_a/b$ and $\varepsilon_c>c_a/b$, $m^{best}(c)=\{1\}$

· When $(1-\varepsilon_v)>c_a/b$ and $\varepsilon_c=c_a/b$, $m^{best}(c) = \begin{cases} \{1\} & \text{if } c\in[0,1) \\ [0,1] & \text{if } c=1 \end{cases}$

· When $(1-\varepsilon_v)>c_a/b$ and $\varepsilon_c<c_a/b$, $m^{best}(c) = \begin{cases} \{1\} & \text{if } c<\lambda_2 \\ [0,1] & \text{if } c=\lambda_2 \\ \{0\} & \text{if } c>\lambda_2 \end{cases}$

where $\lambda_2 = \{(1-\varepsilon_v)b-c_a\}/\{(1-\varepsilon_c-\varepsilon_v)b\}$.

· When $(1-\varepsilon_v)=c_a/b$ and $\varepsilon_c>c_a/b$, $m^{best}(c) = \begin{cases} \{1\} & \text{if } c\in(0,1] \\ [0,1] & \text{if } c=0 \end{cases}$

· When $(1-\varepsilon_v)=c_a/b$ and $\varepsilon_c=c_a/b$, $m^{best}(c)=[0,1]$

· When $(1-\varepsilon_v)=c_a/b$ and $\varepsilon_c<c_a/b$, $m^{best}(c) = \begin{cases} \{0\} & \text{if } c\in(0,1] \\ [0,1] & \text{if } c=0 \end{cases}$

· When $(1-\varepsilon_v)<c_a/b$ and $\varepsilon_c>c_a/b$, $m^{best}(c) = \begin{cases} \{0\} & \text{if } c<\lambda_2 \\ [0,1] & \text{if } c=\lambda_2 \\ \{1\} & \text{if } c>\lambda_2 \end{cases}$

· When $(1-\varepsilon_v) < c_a/b$ and $\varepsilon_c = c_a/b$, $m^{best}(c) = \begin{cases} \{0\} & \text{if } c \in [0,1) \\ [0,1] & \text{if } c = 1 \end{cases}$

· When $(1-\varepsilon_v) < c_a/b$ and $\varepsilon_c < c_a/b$, $m^{best}(c) = \{0\}$

By considering the stable combinations of the best reply correspondences of Agency and Operator, Nash equilibria can be obtained. Here we concentrate on our equilibrium research on non-transitional cases.

I) When $p_v > c_0/(1-\varepsilon_v-\varepsilon_c)$
I-1) When $(1-\varepsilon_v) > c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{\{1\},\{0\}\}$
I-2) When $(1-\varepsilon_v) > c_a/b$ and $\varepsilon_c < c_a/b$, $\{m^*, c^*\} = \{\{1\},\{0\}\}$
I-3) When $(1-\varepsilon_v) = c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{[0,1],\{0\}\}$
I-4) When $(1-\varepsilon_v) = c_a/b$ and $\varepsilon_c < c_a/b$, $\{m^*, c^*\} = \{[0,1],\{0\}\}$
I-5) When $(1-\varepsilon_v) < c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{\{0\},\{0\}\}$
I-6) When $(1-\varepsilon_v) = c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{\{1\},\{0\}\}$
II) When $p_v < c_0/(1-\varepsilon_v-\varepsilon_c)$
II-1) When $(1-\varepsilon_v) > c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{\{1\},\{1\}\}$
II-2) When $(1-\varepsilon_v) > c_a/b$ and $\varepsilon_c < c_a/b$, $\{m^*, c^*\} = \{\{\lambda_1\},\{\lambda_2\}\}$
II-3) When $(1-\varepsilon_v) = c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{[0,\lambda_1),\{0\}\}$, $\{\{\lambda_1\},[0,1]\}$, $\{(\lambda_1,1],\{1\}\}$
II-4) When $(1-\varepsilon_v) = c_a/b$ and $\varepsilon_c < c_a/b$, $\{m^*, c^*\} = \{\{0\},\{0\}\}$
II-5) When $(1-\varepsilon_v) < c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{\{0\},\{0\}\}$, $\{\{1\},\{1\}\}$
II-6) When $(1-\varepsilon_v) = c_a/b$ and $\varepsilon_c > c_a/b$, $\{m^*, c^*\} = \{\{0\},\{0\}\}$

By concentrating on analyses on the meaningful cases of $p_v < c_0/(1-\varepsilon_v-\varepsilon_c)$ [Agency has some incentive to choose Monitor] and $(1-\varepsilon_v) > c_a/b$ [Operator has some incentive to choose Comply], we can get the equilibria given in Table 3.

References

[1] Avenhaus, R.: Monitoring the emission of pollutants by means of the inspector leadership method, *Information and Decision Technologies*, Vol. 16, pp. 229-247, 1990.

[2] Downing, P. and W. D. Watson (1974), The Economics of Enforcing Air Pollution Controls, Journal of Environmental Economics and Management, Vol. 1, pp. 219-236.

[3] Fukuyama, K., K. W. Hipel, and D. M. Kilgour (1994), A Game-Theoretic Analysis of the Effectiveness of Self-Reporting Systems for the Enforcement of Environmental Regulations, in Proceedings of Fourth Stockholm Water Symposium, held in Stockholm, Sweden, August 9-13, 1994, pp. 203-217.

[4] Fukuyama, K., D. M. Kilgour, and K. W. Hipel (1994), Systematic Policy Development to Ensure Compliance to Environmental Regulations, IEEE Transactions on Systems, Man, and Cybernetics, Vol. 24, No. 9, pp. 1289-1305.

[5] Harford, J. D. (1978), Firm Behavior under Imperfectly Enforceable Pollution Standards and Taxes, Journal of Environmental Economics and Management, Vol. 5, pp. 26-43.

[6] Harford, J. D. (1987), Self-Reporting of Pollution and the Firm's Behavior under Imperfectly Enforceable Regulations, Journal of Environmental Economics and Management, Vol. 14, No. 3, pp. 293-303.

[7] Harrington, W. (1988), Enforcement Leverage When Penalties are Restricted, Journal of Environmental Economics and Management, Vol. 37, pp. 29-53.

[8] Kaplow, L. and S. Shavell (1994), Optimal Law Enforcement with Self-Reporting of Behavior, Journal of Political Economy, Vol. 102, No. 3, pp. 583-606.

[9] Kilgour, D. M., L. Fang, and K. W. Hipel (1992), Game-Theoretic Analysis of Enforcement of Environmental Laws and Regulations, Water Resources Bulletin, Vol. 28, No. 1, pp. 141-153.

[10] Linder, S. H. and M. E. McBride (1984), Enforcement Costs and Regulatory Reform – The Agency and Firm Response, Journal of Environmental Economics and Management, Vol. 11, No. 4, pp. 327-346.

[11] Malik, A. S. (1993), Self-Reporting and the Design of Policies for Regulating Stochastic Pollution, Journal of Environmental Economics and Management, Vol. 24, No. 3, pp. 241-257.

[12] Russell, C. S. (1990), Game Models for Structuring Monitoring and Enforcement Systems, Natural Resources Modeling, Vol. 4, No. 2, pp. 143-173.

[13] Scholz, J. T. (1984a), Cooperation, Deterrence, and the Ecology of Regulatory Enforcement, Law and Society Review, Vol. 18, No. 2, pp. 179-224.

[14] Scholz, J. T. (1984b), Voluntary Compliance and Regulatory Enforcement, Law and Policy, Vol. 6, pp. 385-404.

[15] Viscusi, W. K. and R. J. Zeckhauser (1979), Optimal Standards with Incomplete Enforcement, Public Policy, Vol. 27, No. 4.